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OPINION PIECE

Conservation physiology can inform threat assessment and recovery planning processes for threatened species

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ABSTRACT: Conservation physiology has emerged as a discipline with many success stories. Yet, it is unclear how it is currently integrated into the activities of the IUCN and other bodies which undertake international, national, or regional species threat assessments and work with partners to develop recovery plans. Here we argue that conservation physiology has much to offer for the threat assessment process and we outline the ways in which this can be operationalized. For instance, conservation physiology is effective in revealing causal relationships and mechanisms that explain observed patterns, such as population declines. Identifying the causes of population declines is a necessary precursor to the design of actions to reverse or mitigate such threats. Conservation physiology can also identify complex interactions and support modeling activities that consider emerging threats. When a population or species is deemed threatened and recovery plans are needed, physiology can be used to predict how organisms will respond to the conservation intervention and future threats. For example, if a recovery plan was focused on translocation, understanding how to safely translocate organisms would be necessary, as would ensuring that the recipient habitat provides the necessary environmental characteristics to meet the fundamental physiological needs/tolerances of that organism. Our hope is that this paper will clarify ways in which physiological data can make an important contribution to the conservation activities of bodies like the IUCN that are engaged in threat assessment and recovery of endangered organisms. Although we focus on activities at the international scale, these same concepts are relevant and applicable to national and regional bodies.

KEY WORDS: Endangered species · Physiology · IUCN · Threat assessments · Recovery planning · Conservation

INTRODUCTION

In its simplest form, conservation physiology is defined as ‘the study of physiological responses of organisms to human alteration of the environment that might cause or contribute to population declines’

(Wikelski & Cooke 2006, p. 38). It involves the application of physiological concepts, knowledge, and tools to identify and solve conservation problems (Cooke et al. 2013). A recently developed conceptual framework for conservation physiology clearly articulates the pathways in which physiology can inform

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conservation policy and practice (Coristine et al. 2014). While a range of other endpoints may be used (e.g. diversity, reproductive output, size structure, etc.), measurements of population declines are of crucial importance for threat assessments conducted by entities such as the International Union for Conservation of Nature and Natural Resources (IUCN) as part of the Red List process (Mace et al. 2008). Scientifically based determination of the threat status of a given species or population is a key step in order to allocate necessary resources and apply appropriate conservation interventions, ranging from policy to hands-on *in situ* and *ex situ* conservation actions (Rodrigues et al. 2006, Vié et al. 2009). To prevent future declines, or reverse current population declines, we must first understand the underlying causes of such declines (Boersma et al. 2001). Physiology can provide valuable causal information by helping identify how organisms acquire, metabolize, and allocate resources. Furthermore, physiology can help us understand how organisms maintain homeostasis and adapt to changing environments. Thus, physiology can be incorporated into a mechanistic framework to determine how natural and anthropogenic stressors may be affecting organisms.

Here, we aim to describe how physiology may be applied to various threat assessment components and recovery planning processes defined by the IUCN. We present specific case studies to illustrate the use of conservation physiology in real world examples, as well as to further demonstrate where physiology could assist threat assessments and recovery planning. The case studies were selected to yield taxonomic and geographic diversity. We finish by presenting a framework suggesting how conservation physiology may assist in assigning status, along with the important limitations to consider along the process. Although we focused on the IUCN, our proposed approach is equally relevant to other international, national and regional threat assessment processes, such as the Climate Change Vulnerability Index developed by NatureServe (www.natureserve.org/conservation-tools/climate-change-vulnerability-index).

APPLYING PHYSIOLOGY TO THREAT ASSESSMENTS AND RECOVERY PLANNING

Global biodiversity loss due to human activities is occurring at a rate comparable to previous global mass extinctions (Barnosky et al. 2011). To track species vulnerability, organizations such as the

IUCN rely heavily on population size and distribution information, i.e. geographical distribution and the extent of fragmentation among populations (Hoffmann et al. 2008). Criteria used by the IUCN to determine the threat status of species as Vulnerable, Endangered or Critically Endangered are as follows: (A) population size reduction, (B) geographic range (extent and area of occupancy), (C) small population size and decline, (D) very small or restricted population, and (E) quantitative analysis for extinction risk (IUCN 2012; Fig. 1). The threat levels identified above are distinguished using data that suggest levels of decline reversibility and suspension, or the elimination of mechanisms responsible for triggering the decline.

This paper illustrates the various ways in which some common physiological tools can be implemented into the IUCN threat assessments, and thus help in assigning status (Fig. 1). We acknowledge that there are more ways to apply physiological tools than we describe, and that this list of physiological tools and their applications is dynamic and subject to change as physiological techniques evolve. Furthermore, we acknowledge that much of the physiological data will be most useful when combined with other information (e.g. environmental elements, population estimates). Nonetheless, physiology can provide data on the underlying issues that drive species decline, or help predict responses to future threats, and as such may be useful in threat assessments and recovery planning.

Physiological tools applicable to IUCN criteria include comparative, environmental, ecological, neurosensory and cardiorespiratory physiology, environmental toxicology, immunology, chemical communication, bioenergetics and nutrition, locomotor performance, reproduction, and genomics (Fig. 1). Such tools may be used to ‘infer, project, and/or suspect’ (IUCN 2012) a species’ threat level by scaling up individual responses to population response, with the tacit assumption that individual physiological responses are representative of the population. ‘Estimated’ threat may only be applied to very small or restricted populations (Criterion D, Fig. 1) as all individuals must be accounted for (IUCN 2012, Fig. 1); ‘observed’ data are outside the capable scope of conservation physiology.

The assessment process also considers factors such as species habitat, relevant threats and stressors to direct conservation actions and research needs (see www.iucnredlist.org/technical-documents/classification-schemes). Physiology may be helpful for acquiring this information. However, for a species to be

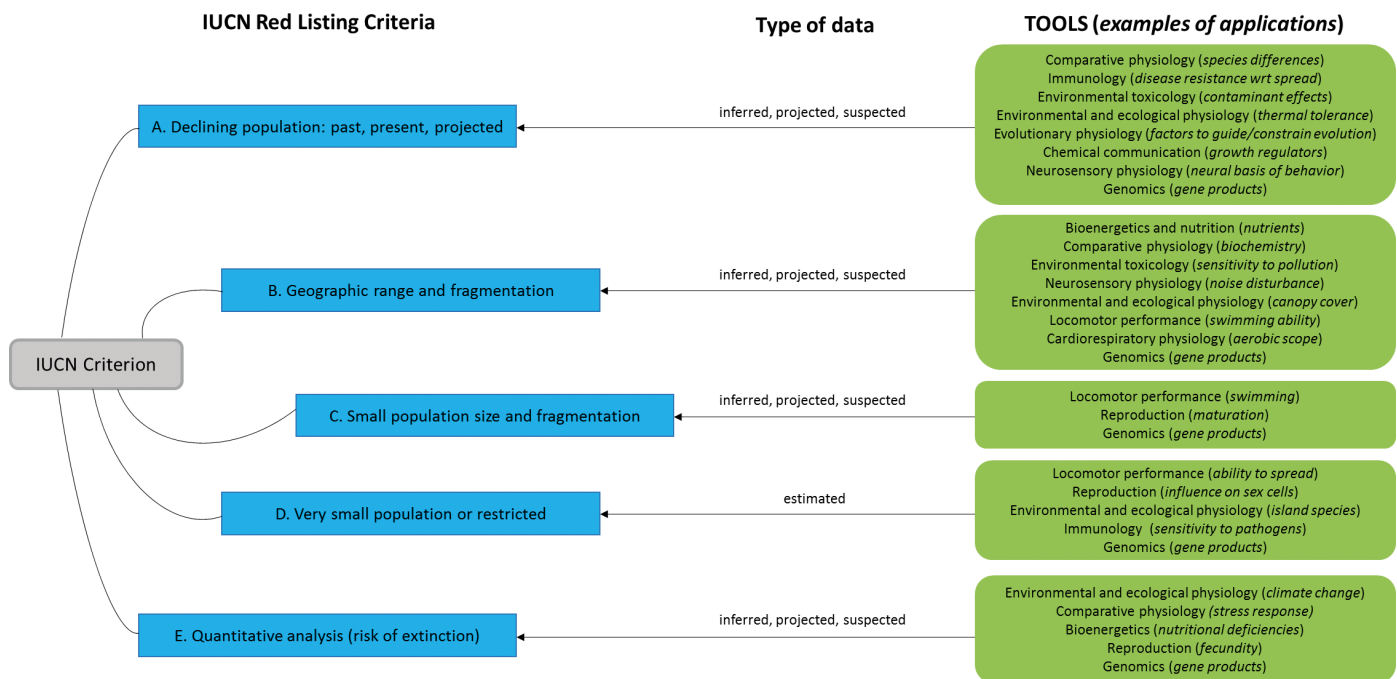


Fig. 1. Use of physiological tools in IUCN threat assessment. Proposed framework on how to use physiological tools (green, with examples in *italics*) to inform the various IUCN criteria (blue)

assigned a higher threat level (i.e. Critically Endangered), population declines must already be observed throughout the species' global range. It is worth acknowledging that there are inherent challenges associated with accurate population assessments of wild organisms, especially those that are rare, such that there can be significant uncertainty with threat assessments (Colyvan et al. 1999).

While recording overall population declines provides critical information for conservation, incorporating the physiological mechanisms driving changes in populations would provide a mechanistic understanding of how threats impact an organism's ability to obtain energy, survive, and reproduce. This information can be used to forecast how a plant or animal may respond to prolonged exposure to similar or higher magnitude anthropogenic stressors (Fig. 1). In this way, physiology can improve the scientific basis for assigning threat status using most criteria, and likely increase the probability of developing successful recovery plans. In addition, characterizing physiological responses to anthropogenic stressors could provide managers with early warning signs that population declines may occur (Criterion A, Fig. 1). Better understanding of environmental and ecological physiology may also strengthen predictions of population-level responses to anthropogenic stressors (Criteria A, B & E, Fig. 1). For example, Catenazzi et

al. (2014) demonstrated that thermal stress increases susceptibility to pathogen-induced mortality in South American amphibians, highlighting potential for population crashes in climate warming scenarios. In recovery programs, knowledge of reproductive physiology and consequent habitat requirements can improve conservation strategies, including captive breeding programs (Criteria C, D & E, Fig. 1; O'Brien & Robeck 2010).

REAL WORLD SCENARIOS: APPLYING PHYSIOLOGY FOR IUCN THREAT ASSESSMENTS

Endemic species of Hawaii and Madagascar

Geographic isolation, habitat heterogeneity, and climatic variation of islands produce a disproportionate fraction of endemic taxa which are susceptible to anthropogenic threats (Roberson 2006, Whittaker & Fernández-Palacios 2007). Use of physiological tools may elucidate adaptive potential and ecological susceptibility of endemic island taxa to climate change, habitat reduction and invasive species using all IUCN criteria. Use of physiological tools may also increase our capacity to assess the status of island taxa with restricted population sizes (Criterion D, Fig. 1).

The IUCN emphasized the need for data on endemic amphibian, reptilian and plant taxa (Callmander et al. 2005, Giam et al. 2010) in biodiversity hotspots Hawaii and Madagascar. Recent work has focused on status assessments for expansion of protected areas to maximize conservation of endemic richness within contrasting habitats in both areas (Callmander et al. 2007, Andreone et al. 2008, Miller & Porter Morgan 2011, Jenkins et al. 2014, Rakotoarinivo et al. 2014). Physiological research is helping to address eco-physiological performance and functions not supported by protected areas that influence population dynamics of vulnerable plant, amphibian and reptilian species (Vallan 2002, Andreone et al. 2008, Blaustein et al. 2012). For example, to understand colonization and distribution mechanisms in order to model and manage impacts of invasions, *in situ* photosynthetic capacity of introduced plants species in Hawaii's endangered dry forest were compared; species-specific physiological and morphological traits were strongly correlated to plant biomass, but photosynthetic physiology was functionally equivalent (Cordell et al. 2002).

Another important factor that must be considered in order to conserve endemic species of geographically isolated regions is species mutualism (Colwell et al. 2012). For example, seed-dispersal mutualisms between endemic plants and reptile species provide an important approach to investigate cause-and-effect relationships between these 2 taxa, given that the nutritional needs and digestive processes of the reptiles are fundamental to the plants (Ruxton & Schaefer 2012). Endemic lizards and other tropical ectotherms, for instance, are important seed dispersers in island habitats (Hansen & Muller 2009). Understanding such mutualisms may elucidate population dynamics useful to Red List assessments.

Oxidative stress as a population health indicator in Antarctic penguins

Antarctica is home to the gentoo penguin *Pygoscelis papua* and the Adélie penguin *P. adeliae* and is an area showing great environmental vulnerability to climate change, especially due to increasing water temperature, decreasing ice cover and diminished krill populations (Bennett et al. 2015). Both penguin species are listed as Near Threatened by the IUCN (Beaulieu et al. 2015, D'Amico et al. 2016, IUCN 2016), though they demonstrate contrasting demographic trends within different regions of Antarctica (Beaulieu et al. 2013).

Recently, the use of oxidative stress markers to estimate population health of animal populations has shown great promise for conservation (Beaulieu et al. 2013, Beaulieu & Constantini 2014). Populations with poor antioxidant defenses may decline under environmental conditions where pro-oxidants are favored (Noguera et al. 2012, Beaulieu et al. 2013). Beaulieu et al. (2013) found that penguins in increasing populations had higher antioxidant defenses than those in decreasing populations. Decreased antioxidant capacity has several implications, most prominently, reductions in fitness, fertility and survival (Bize et al. 2008, Beaulieu et al. 2013). Monitoring oxidative stress in Antarctic penguins may provide early warning indicators of the impacts of climate change or other stresses, and subsequently project or infer population declines (Criterion A, Fig. 1).

Reproduction, genomics and nutrition: conservation of kiwis in New Zealand

Since the arrival of Europeans in New Zealand, the island's 5 endemic species of kiwi *Apteryx* spp. have faced a rapid decrease in population size, and all were initially labeled as Endangered or Critically Endangered by the IUCN (McLennan 1988, Holzapfel et al. 2008). Deforestation and the introduction of predatory mammals (specifically stoats and dogs) have been the primary threats to kiwi survival (McLennan 1988, McLennan et al. 1996, Basse et al. 1999). Research on kiwi physiology has had great success in informing IUCN threat assessment (Criteria C, D & E, Fig. 1) and implementing recovery plans. One of New Zealand's major conservation efforts, Operation Nest Egg (ONE), has depended primarily on physiological data to inform its research protocol (Colbourne et al. 2005, Holzapfel et al. 2008). Kiwi reproduction is unique amongst birds and characterized by large egg sizes (taking up to 15 to 20% of the female's body cavity), rapid egg development (30 d from conception to laying), small clutches (generally a single egg), long incubation periods (74 to 84 d) shared by both male and female, and lack of parental-provided chick feeding (an external yolk sac provides nutrition for the first 10 d after hatching) (Colbourne 2002, Robertson et al. 2011). Physiological data on kiwi reproduction led to development of the ONE protocol to boost the kiwi populations. The protocol begins with removal of eggs from nests (located via radio telemetry of adult pairs), which are then incubated, hatched and the young reared in a secure *ex situ*

environment (McLennan 1988, Colbourne et al. 2005, Holzapfel et al. 2008). Young are released into a predator-free zone to learn effective foraging techniques prior to release into the wild as adults (Robertson et al. 2011). Genetics of the reared kiwis determine where they are released as adults to ensure genetic diversity and survival (Colbourne et al. 2005, Le Duc et al. 2015). This translocation program informed by physiological data has aided in the reclassification of 2 kiwi species to Vulnerable, and a third species to Near Threatened (IUCN 2016). Importantly, physiology was one of several tools (i.e. molecular genetics, behavioural assays) used in this process.

Migratory fish, river modifications, and physiological tolerances

Many migratory freshwater fish are in a state of global decline (IUCN 2016) and require immediate status assessments to inform conservation actions. Migratory fish exhibit complex life histories, often using both freshwater and marine environments throughout their life cycle (Bemis & Kynard 1997). Complex life histories can exacerbate challenges associated with applying IUCN Red List Criteria A, B and E (Fig. 1) (Liermann et al. 2012, Jacoby et al. 2014, 2015). Use of physiological tools may identify how hydrological impacts influence successful recruitment and address knowledge gaps related to specific life-stage survival, thus helping to infer or project rates of population decline (Jacoby et al. 2015). Physiological tools may further elucidate mechanisms that influence population level responses to natural (e.g. thermal increase) and artificial (e.g. hydroelectric dam) riverine modifications (Cooke 2008), providing data that may inform all assessment criteria. For example, Verhille et al. (2014) assessed the swimming capacity of larval sturgeon to reduce entrainment risk in water-diversion structures, a known factor in population decline. Whiterod (2013) used bioenergetics to develop a swimming-performance model that identified susceptibility of juvenile Murray cod *Maccullochella peelii* to hydroelectric operations in the Murray Darling basin, Australia (Kearney & Kildea 2001). With elevated conservation concerns surrounding the status of endangered migratory freshwater fish (Jacoby et al. 2014), use of sensory, neurophysiological, eco-physiological and biotelemetry tools may expedite the acquisition of data to accurately determine threat levels.

LIMITATIONS TO THE USE OF CONSERVATION PHYSIOLOGY IN THREAT ASSESSMENTS

Although conservation physiology is broadly applicable to understanding conservation threats and developing solutions, there are some key limitations to integrating physiological knowledge and tools into IUCN threat assessments. Many candidate species at risk exist in small, isolated populations and must be studied in the wild, whereas many physiological tools are suited to laboratory or captive animal applications. Working with wild animals, particularly with sensitive species, means that the suite of physiological tools available for sampling may be limited to assays that are non-lethal and minimally invasive, excluding some relevant tests that require lethal sampling or invasive surgery (e.g. whole body cortisol, organ histology, muscle energetics). In some cases, it may be possible to use surrogate species for developing these concepts (Wenger 2008), although this approach should be used with caution. There are increasing examples of minimally invasive biopsies that can be taken from wild animals, and many physiological tools are being adapted for use in the field (e.g. point-of-care sampling devices; Stoot et al. 2014). However, measurements of physiological stress responses (e.g. primary stress response, heart rate, oxygen consumption) must consider the time-course of changes in the response, comparing baseline, peak, and return to resting values. Baseline responses are logistically difficult to generate because animals must be captured and handled to obtain samples, creating an inherent stress response bias (Pankhurst 2011). This may prove particularly difficult in the context of regional assessments in developing countries where such technical capacity may not exist.

Furthermore, to apply physiological data to a population, the number of individuals sampled must be sufficiently large to account for potential variation in factors such as age, sex, and size. Lastly, limitations may include temporal or financial factors. Physiological work can be time consuming and expensive, and when balanced against the need for an immediate listing decision based on current information (e.g. populations in severe decline), there may also be situations where physiological information is not justified before listing and/or action must begin.

CONCLUSIONS AND OUTLOOK TO THE FUTURE

Understanding physiological responses is essential to determine how a species may respond to stressors.

In the wild, species are often exposed to more than a single stressor at a time (Boonstra 2013), and the extent of their combined or cumulative impacts can be elucidated using physiology, which provides information that one cannot necessarily observe through basic behavioral studies. In conservation, physiology is most relevant when making predictions of future responses to known threats. For example, an organism's physiology constrains the range of environments in which it can live (Seebacher & Franklin 2012) and can help us understand how habitat loss or fragmentation may affect it. Physiological responses to known threats such as pollutants and climate change may also provide valuable data needed to make informed threat assessments. Physiology can supplement ecological and behavioral data for species where more research is needed, but approaches and techniques to obtain such data are limited (e.g. qualitative observations). As such, physiology is especially useful for recovery planning. Additionally, physiology can be integrated into models used to estimate probability of extinction (Criterion E, Fig. 1) and render this assessment more reliable, though assigning probability of extinction requires more data than physiology alone can provide. We acknowledge that physiological data cannot inform all criteria without making some assumptions, or combining the data with other available information (e.g. knowledge on the distribution of environmental variables which may be causative factors for physiological outcomes). However, new threats, or threats that are still poorly understood (e.g. climate change) may require the application of new techniques and approaches to informing IUCN threat assessments, which conservation physiology can provide. Combined with other techniques, the use of physiology can provide us with a powerful tool to assess threats and plan recovery strategies.

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